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Horppila, Jukka

2019

Horppila , J , Holmroos , H , Niemistö , J & Tammeorg , O 2019 , ' Lake catchment characteristics and external P load - cultivated area/lake area ratio as a tool for evaluating the risk of eutrophication from land use information ' , Boreal Environment Research , vol. 24 , pp. 13-23 . < http://www.borenv.net/BER/ber241-6.htm >

http://hdl.handle.net/10138/304606

unspecified
publishedVersion

Lake catchment characteristics and external P load – cultivated area/lake area ratio as a tool for evaluating the risk of eutrophication from land use information

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Received 6 Aug. 2018, final version received 6 Mar. 2019, accepted 21 Mar. 2019

Horppila J., Holmroos H., Niemistö J. & Tammeorg O. 2019: Lake catchment characteristics and external P load — cultivated area/lake area ratio as a tool for evaluating the risk of eutrophication from land use information. *Boreal Env. Res.* 24: 13–23.

The effects of land use on external P load (L_P), critical P load (L_C) and on L_P/L_C of 27 lakes in Finland were examined with regression analyses. Catchment area to lake area ratio (A_C/A_L), cultivated catchment area to lake area ratio (A_F/A_L) and the percentage of cultivated land in the catchment ($F_{\%}$) were used as independent variables. We studied whether these parameters can be used to estimate the risk of exceeding the critical P load ($L_P/L_C > 1$). All three parameters had a positive effect on L_P and L_P/L_C. Compared with A_C/A_L and $F_{\%}$, A_F/A_L had a higher coefficient of determination in predicting L_P and L_P/L_C. This was because A_C/A_L does not include land use variations in catchments and $F_{\%}$ does not include information on catchment size, while A_F/A_L includes information on both. Critical P load was exceeded when $A_F/A_L >$ 1.63. A_F/A_L can be a useful and simple tool for evaluating the risk of lake eutrophication.

Introduction

Anthropogenic eutrophication is one the most prevalent environmental problems in freshwater ecosystems (Smith 2003, Schindler 2006). In a large number of lakes, eutrophication has deteriorated the possibilities for domestic water use and recreation through its effects on water quality and biota (Carpenter *et al*. 1998). In lakes, phosphorus (P) is commonly the main nutrient limiting primary production (Schindler 1977). Therefore, controlling the human-induced external load of P to lakes is one of the main challenges in lake management.

Knowledge on the ability of lakes to withstand the external load of P is needed. Such knowledge can be used by decision-makers (e.g. municipalities, industry or agriculture) to regulate the P load from various sources. The most widely used methods for this purpose have been the critical load model by Vollenweider (Vollenweider 1976) and its modifications (e.g. Dillon and Rigler 1974, Kirchner and Dillon 1975, Canfield and Bachmann 1981, Ahlgren *et al*. 1988). Using these models, P and chlorophyll a concentrations of lakes are predicted using lake characteristics, such as mean depth and water residence time, with data on P load. Additionally, many dynamic phosphorus models were developed (Ahlgren *et al*. 1988, Janse *et al*. 2010). In general, all models are sensitive to uncertainties in external load values (Reckhow 1979, Janse

Editor in charge of this article: Hannu Marttila

et al. 2010). This is a challenge especially in catchment areas where diffuse P load dominates. Compared with point load, for example from industrial, municipal and wastewater treatment plants, the estimation of diffuse load is more problematic (Carpenter *et al*. 1998). This is a severe problem because diffuse load from agricultural and forestry areas is also more difficult to control than point load and it has nowadays become the dominant component in regulating the external load and water quality of numerous lakes (Soranno *et al*. 1996, Carpenter *et al*. 1998, Palviainen *et al*. 2015). Therefore, several attempts have been made to predict nutrient load and water quality from land use information (Dillon and Kirchner 1975, Reckhow *et al*. 1980, Johnes 1996, Soranno *et al*. 1996, Ekholm *et al*. 2000, Tong and Chen 2002, Nielsen *et al*. 2012). Such models often become complicated because they should include numerous parameters such as soil type, catchment slopes, livestock numbers, crop types and human population data (Meeuwig and Peters 1996, Ekholm *et al*. 2000, Bennion *et al*. 2005, Arhonditsis *et al*. 2007). Models often require so extensive input data, that they may be unsuitable for end-users performing risk assessment in practice (Heckrath *et al*. 2008). Therefore, many attempts were also made to provide simple, user-friendly tools for assessing P load from catchments with limited data (Heckrath *et al*. 2008). These indices typically account for both source and transport factors and they are used to assess where P leaching occurs in the catchment (Sharpley *et al*. 2001, Veith *et al*. 2003, Heckrath *et al*. 2008).

In the present study, we aimed to develop a simple tool to assess the risk of exceeding the critical P load of lakes. We explored the possibility to combine the critical load concept and the catchment land use information in a novel way. We hypothesized that it is possible to use the coverage of cultivated land in the catchment to estimate the risk of exceeding the critical P load. This can be possible, as the effect of cultivated land on the external nutrient load often dominates compared with other forms of land use (Ekholm *et al*. 2000, Reed-Andersen *et al*. 2000, Bechmann *et al*. 2003). We tested a new approach by relating the area of cultivated land in square kilometers to the area of the recipient lakes. If the predictive value of the new approach is high enough, the method could be used in planning the land use in catchments. Our tool was compared with a previously used catchment area–lake area relationship and percentage coverage of cultivated land in the catchment.

Materials and methods

Data were collected from 27 lakes in Finland (Table 1). The lakes were chosen randomly among those where suitable data (P load measurements based on discharge and P concentration measurements and thus independent on land use information) were available. The trophic state of the lakes varied from mesotrophic to hypereutrophic, lake area from 0.3 km^2 to 155 km^2 and lake mean depth from 1.2 m to 20.8 m (Table 1). The catchment area (A_C) of the lakes (lake excluded) varied between 1.1 km^2 and 896 km^2 (mean 179 km^2) and percentage of cultivated and pastured land together ($F_{\%}$) in the catchments between 5% and 31%. For $F_{\%}$, cultivated areas dominated with a mean coverage of 16% while the coverage of pastured areas averaged only 0.1%. The lake percentage ($L_{\%}$) in catchment areas varied between 0% and 7.9% (Table 1). To avoid the scale effect, the mean catchment area (excluding the lake) in the present dataset was 179 km^2. The load of total P concentration (P_{tot}) per unit catchment area may decrease with increasing catchment area, but this phenomenon is significant only for catchments < 20 km^2 (Prairie and Kalff 1986, Ekholm *et al*. 2000). In the present dataset, 5 out of 27 lakes had a catchment area smaller than 20 km^2.

The nutrient load entering lakes is usually dependent on the relationship between A_C and the lake area (A_L). The higher the catchment area in relation to the lake area (A_C/A_L), the higher the nutrient load per unit area of the lake (e.g., Kalff 2003). On the other hand, land use in the catchment has an effect on nutrient leaching and $F_{\%}$ has often been used to characterize the load from catchments (Rekolainen 1989, Ekholm *et al*. 2000). $F_{\%}$ reflects the nutrient load from the catchment, while A_C/A_L gives an impression on the overall load entering the lake (Rekolainen 1989, Ekholm *et al*. 2000).

Because A_C/A_L does not account for land use variations between catchments and $F_{\%}$ does not include information on catchment size, we combined the information given by these two parameters. A_C and $F_{\%}$ were combined to create a new parameter, A_F/A_L, which gives the cultivated area in the catchment (A_F) in relation to the surface area of the lake:

$$A_F/A_L = [(A_C \times F_{\%})/100]/A_L. \qquad (1)$$

The effect of A_C/A_L, $F_{\%}$, and A_F/A_L on external P load (L_P) and on the ratio of L_P and critical P load (L_C) was studied with linear regression analysis. The data were ln-transformed data to improve normality. If the studied catchment parameters have a significant effect on L_P/L_C, their values leading to $L_P/L_C > 1$ can be considered critical for the lake. The coefficient of determination (R^2) obtained from the regressions were also used to evaluate the relationships between catchment characteristics and P load (Nielsen *et al*. 2012). The catchment area of each lake, and the land use in the catchment was determined with the VALUE tool provided by the Finnish Environment Institute (http://paikkatieto.ymparisto.fi/value). The tool derives land use variables and lake percentages taken from Coordination of Information on the Environment (CORINE 2012) land cover data. The national CORINE 2012 database for Finland has a spatial resolution of 25 m. $F_{\%}$ and A_F/A_L included areas that were defined by the CORINE data as cultivated land or pasture. The values of L_P and water discharge (q_s), as well as total P concentrations (P_{tot}) were obtained from the HERTTA database of the Finnish Environment Institute (https://wwwp2.ymparisto.fi/scripts/hearts/welcome.asp) and from the reports of the local environmental authorities (Table 2). For

Table 1. Characteristics of the study lakes and their catchment areas. The lake is not included in its catchment area.

Lake	Location	A_L (km^2)	Mean depth (m)	Max depth (m)	A_C (km^2)	$F_{\%}$	$L_{\%}$
Bodominjärvi	60°15´13´´N, 24°40´17´´E	4.1	4.3	12.7	27.3	19	2.0
Enäjärvi	60°20´17´´N, 24°21´38´´E	4.9	3.2	9.1	29.1	22	0
Harvanjärvi	63°63´69´´N, 27°57´33´´E	2.1	3.9	15.2	7.1	13	0
Hiidenvesi	60°22´30´´N, 24°11´31´´E	30.3	6.7	33.0	896.0	16	5.7
Hirvijärvi	60°40´4´´N, 24°37´41´´E	4.3	14.0	29.6	22.0	10	2.3
Jalanti	61°9´32´´N, 23°45´4´´E	6.4	2.7	6.1	740.0	19	5.1
Karhujärvi	60°13´32´´N, 24°16´55´´E	1.9	2.2	4.9	228.0	15	6.7
Katumajärvi	60°59´19´´N, 24°31´3´´E	3.8	7.1	18.9	44.2	8	6.7
Kymijärvi	60°58´12´´N, 25°47´56´´E	6.5	2.6	11.0	34.0	6	6.5
Kyynäröjärvi	61°7´24´´N, 24°59´25´´E	0.3	1.3	3.0	28.0	26	0.5
Köyliönjärvi	61°6´58´´N, 22°20´53´´E	12.5	3.0	12.8	133.0	30	0
Loppijärvi	60°41´26´´N, 24°25´27´´E	11.8	1.8	6.7	70.0	14	1.5
Matalajärvi	60°15´1´´N, 66″24°41 54´´E	0.7	1.2	2.4	3.8	17	0.0
Nuutajärvi	61°02´6´´N, 23°27´25´´E	1.8	1.9	2.3	87.0	17	4.4
Oksjärvi	60°79´58´´N, 23°94´56´´E	3.1	2.6	7.0	14.0	5	1.2
Parkanonjärvi	61°59´2´´N, 23°1´65´´E	4.7	6.8	22.0	707.0	7	7.0
Pusulanjärvi	60°27´28´´N, 23°58´51´´E	2.1	4.9	10.6	221.0	15	7.9
Puujärvi	60°15´15´´N, 23°42´58´´E	6.4	8.3	21.7	21.0	15	2.3
Pyhäjärvi, Orimattila	60°42´46´´N, 26°0´14´´E	12.9	20.8	68.0	445.0	31	3.2
Pyhäjärvi, Säkylä	60°59´20´´N, 22°18´8´´E	155.0	5.5	26.2	451.0	21	0.1
Rusutjärvi	60°42´72´´N, 24°97´99´´E	1.3	2.5	3.6	3.3	24	0
Savijärvi	60°21´36´´N, 25°20´5´´E	0.4	1.6	2.6	1.1	15	0.3
Tiiläänjärvi	60°32´26´´N, 25°42´11´´E	2.1	4.4	10.3	36.0	22	2.1
Tuusulanjärvi	60°26´34´´N, 25°3´37´´E	5.9	3.2	10.0	83.0	28	0.9
Villikkalanjärvi	60°46´3´´N, 26°2´14´´E	7.1	2.9	8.9	404.0	31	1.2
Vuonisjärvi	63°8´41´´N, 30°6´7´´E	0.7	1.5	5.3	20.0	11	1.5
Äimäjärvi	61°3´14´´N, 24°9´51´´E	8.5	2.9	9.0	85.0	13	2.5

most lakes, the values of q_s included direct measurements from lake inlet streams, while for some of the lakes, q_s was calculated based on reported water retention time and lake volume. Values for L_P were calculated using water discharge data and P concentration measurements using an approach most suitable for lakes with the given number of available observations (Jones *et al*. 2012). The P load from the catchments accounted also for the contribution from unmonitored areas by areal extrapolation (Ekholm *et al*. 1997, Tammeorg *et al*. 2017). The number of L_P estimates varied lake to lake and mostly covered several recent years with monthly measurements. The critical P load (L_C) is determined by the relationship of lake mean depth and water residence time, or by the relationship of inflow water discharge and lake area; termed as areal water load, q_s (e.g., Brett and Benjamin 2008). In this study, L_C (mg P m^{-2} a^{-1}) was calculated as:

$$L_C = 0.174 q_s^{0.469}. \quad (2)$$

The equation (Vollenweider 1976, as cited in Eloranta 2005) has frequently been used in estimating the critical load of Finnish lakes (e.g., Karvonen 2007, Hagman 2011, Pulkkinen 2014). L_P was expected to increase with increasing A_C/A_L and A_F/A_L. On the other hand, L_C increases with increasing A_C/A_L, because q_s usually increases and water residence time decreases with increasing A_C/A_L. Therefore, to explore the factors determining the effect of A_C/A_L, $F_\%$ and A_F/A_L on L_P/L_C, their relationship with q_s of the studied lakes was studied by linear regression analysis. Since lake area (A_L) is included in L_C, A_C/A_L and A_F/A_L, regression analysis was used to explore whether A_L had any effect on L_P/L_C. To track the possible scale effect among the studied catchments, the relationship between catchment area and L_P per unit catchment area (L_P divided by the area of the catchment) was also analyzed with regression analysis. Additionally, the relationship of the percentage coverage of lakes ($L_\%$) and L_P/L_C was studied with regression analysis. This was done because lake coverage can substantially affect the retention of nutrients in the catchment areas (e.g., Röman *et al*. 2018).

Results

The external P load (L_P) of the lakes varied between 25 mg m^{-2} a^{-1} (Puujärvi) to 5200 mg m^{-2} a^{-1} (Jalanti), with the mean value being 1065 mg m^{-2} a^{-1} (Table 2). The epilimnetic concentration of P_{tot} ranged from 9 µg l^{-1} to 114 µg l^{-1} (mean 53 µg l^{-1}) with the lowest and highest values occurring in Hirvijärvi and Matalajärvi, respectively (Table 2). The critical P load (L_C) varied between 166–1058 mg m^{-2} a^{-1} (Table 2). L_P exceeded L_C in 17 out of 27 lakes.

All the three studied catchment parameters, $F_\%$, A_C/A_L and A_F/A_L, had a significant effect on L_P (Fig. 1). The coefficient of determination was the highest with A_F/A_L and the lowest with $F_\%$ (Fig. 1). All three parameters had also a significant effect on L_P/L_C (Fig. 2). The coefficient of determination was again the highest with A_F/A_L and the lowest with $F_\%$ (Fig. 2). According to the regression equation between A_F/A_L and L_P/L_C, the external load exceeded the critical load (L_P/L_C) when ln (A_F/A_L) > 0.49; i.e., when $A_F/A_L > 1.63$ (Fig. 2). The threshold value of $F_\%$ was 12.9%.

The areal water load, q_s, was dependent on A_C/A_L ($F_{1,25} = 145.12$, $R^2 = 0.85$, $p < 0.001$) and A_F/A_L ($F_{1,25} = 108.18$, $R^2 = 0.81$, $p < 0.001$), while the effect of $F_\%$ on q_s was insignificant ($F_{1,25} = 1.15$, $R^2 = 0.04$, $p = 0.293$). $L_\%$ had no effect on L_P/L_C ($F_{1,25} = 0.42$, $R^2 = 0.02$, $p = 0.521$). Neither did lake area A_L have any effect on L_P/L_C ($F_{1,25} = 0.67$, $R^2 = 0.02$, $p = 0.419$). External P load per unit area of the catchment was not dependent on the catchment size ($F_{1,25} = 0.95$, $R^2 = 0.04$, $p = 0.337$). A_F/A_L and $F_\%$ had a significant relationship with the epilimnetic P_{tot} concentration in the lakes while there was only a marginal effect of A_C/A_L on P_{tot} (Table 3).

Discussion

Corroborating previous studies, the results demonstrated that the external P load of lakes (L_P) increased with increasing A_C/A_L (Kortelainen 1993, Kalff 2003). A_F/A_L had a strong effect on L_P and a higher coefficient of determination than A_C/A_L. This was because the values of A_C/A_L included all land use types, most of which have a weaker effect on P load than agricultural areas.

For instance, forests covered 29–78% of the catchment areas included in A_C/A_L. Vuorenmaa *et al*. (2002) estimated that the mean specific load of P from agricultural areas was 110 kg km^{-2} a^{-1}, which was 12 times the load from forested areas (9 kg km^{-2} a^{-1}). Similarly, Rekolainen (1989) has reported that P load from agricultural catchments varies from 90–180 kg km^{-2} a^{-1} in Finland, which is about ten times higher than the value from forested land. A_F/A_L included only cultivated and pastured areas, therefore it had a closer relationship with L_P than A_C/A_L. $F_{\%}$ was also a significant predictor of L_P. The coefficient of determination was, however, clearly lower with $F_{\%}$ than with the other two parameters, because $F_{\%}$ does not take the catchment area into consideration.

The load of P_{tot} per unit catchment area tends to decrease with increasing catchment size (Ekholm *et al*. 2000). With the present dataset, such phenomenon was not detected. This was probably because the scale effect was strong especially in smaller catchments than most of those used in this study (Prairie and Kalff 1986, Ekholm *et al*. 2000). $L_{\%}$ had no effect on L_P/L_C, although the nutrient retention in the catchment area usually increases with increasing cover-

Table 2. The ratio of cultivated area in the catchment and lake area (A_F/A_L), external P load (L_P), critical P load (L_C), L_P/L_C ratio, areal water load (q_s) and concentration of total phosphorus in the epilimnion (P_{tot}) of the study lakes. Sources of the L_P, q_s and P_{tot} values for each lake are given below the table.

Lake	A_F/A_L	L_P (mg m^{-2} a^{-1})	L_C (mg m^{-2} a^{-1})	L_P/L_C	q_s (m a^{-1})	P_{tot} (µg l^{-1})
Bodominjärvi[1,2]	1.26	507	258	1.97	2.3	32
Enäjärvi[1,3]	1.26	323	313	1.03	3.5	98
Harvanjärvi[1,4]	0.46	73	166	0.44	0.9	20
Hiidenvesi[1,5]	4.71	924	481	1.92	8.7	70
Hirvijärvi[1,6]	0.52	57	203	0.28	1.4	9
Jalanti[1,7]	22.07	5200	914	5.69	34.3	63
Karhujärvi[1,8,9]	18.12	4232	920	4.60	34.9	72
Katumajärvi[1,10]	0.96	232	313	0.74	3.5	19
Kymijärvi[1,11]	0.31	48	232	0.21	1.8	24
Kyynäröjärvi[12,13]	28.64	2263	878	2.58	31.6	50
Köyliönjärvi[1,14]	3.18	710	304	2.34	3.3	83
Loppijärvi[1,15,16]	0.82	93	183	0.51	1.1	30
Matalajärvi[1,17]	1.07	338	276	1.23	2.7	114
Nuutajärvi[1,7]	7.59	2700	317	8.52	3.6	110
Oksjärvi[1,18]	0.22	70	209	0.33	1.5	12
Parkanonjärvi[19]	11.06	2128	1058	2.01	47.0	30
Pusulanjärvi[1,20]	15.96	1707	916	1.86	34.5	49
Puujärvi[1,12]	0.49	26	188	0.14	1.2	12
Pyhäjärvi, Orimattila[1,21]	10.61	814	523	1.56	10.5	44
Pyhäjärvi, Säkylä[1,22]	0.61	106	224	0.47	1.7	17
Rusutjärvi[1,23]	0.61	254	338	0.75	4.1	60
Savijärvi[1,24,25]	0.41	260	252	1.03	2.2	80
Tiiläänjärvi[1,12]	3.76	1428	431	3.31	6.9	80
Tuusulanjärvi[1,26,27]	3.94	960	358	2.68	4.7	101
Villikkalanjärvi[1,28]	17.71	2302	671	3.43	17.8	111
Vuonisjärvi[1,29]	3.34	783	635	1.23	15.8	54
Äimäjärvi[1,30]	1.32	283	282	0.81	2.8	42

[1]HERTTA database (2015) [2]Hagman (2010), [3]Taponen (1997), [4]Kauppinen (2007), [5]Hagman (2012), [6]Salo & Harjula (2012) [7]Närvänen *et al.* (2002), [8]Valjus (2011), [9]Valjus (2012), [10]Jutila and Salminen (2006), [11]Järveläinen *et al.* (2012), [12]Tammeorg *et al.* (2017), [13]Kaipainen *et al.* (2002), [14]Paloheimo (2010) [15]Keto and Sammalkorpi (2009), [16]Aaltonen and Jutila (2006), [17]Karvonen (2007), [18]Mäkelä (2016), [19]Skippari *et al.* (2003), [20]Lappalainen (1998), [21]Hämeen vesienhoidon toimenpideohjelma (2015), [22]Ventelä *et al.* (2007), [23]Huuhko & Hanski (2013), [24]Hagman (2011), [25]Riihimäki (2008), [26]Muukkonen (2010), [27]Ojanen (1979), [28]Knuuttila *et al.* (1994), [29]Tossavainen (2014), [30]Kontio (2011)

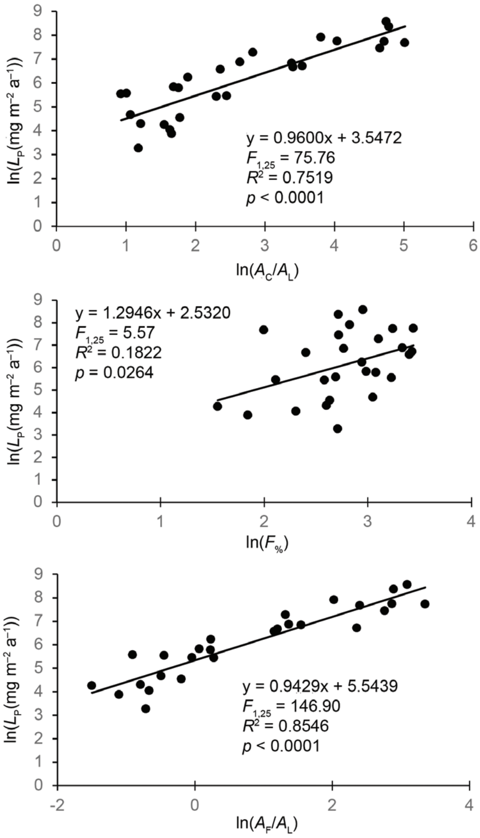

Figure 1. The effect of A_C/A_L (top), $F_{\%}$ (middle) and A_F/A_L (bottom) on external P load (L_P) of the study lakes. The values are ln-transformed.

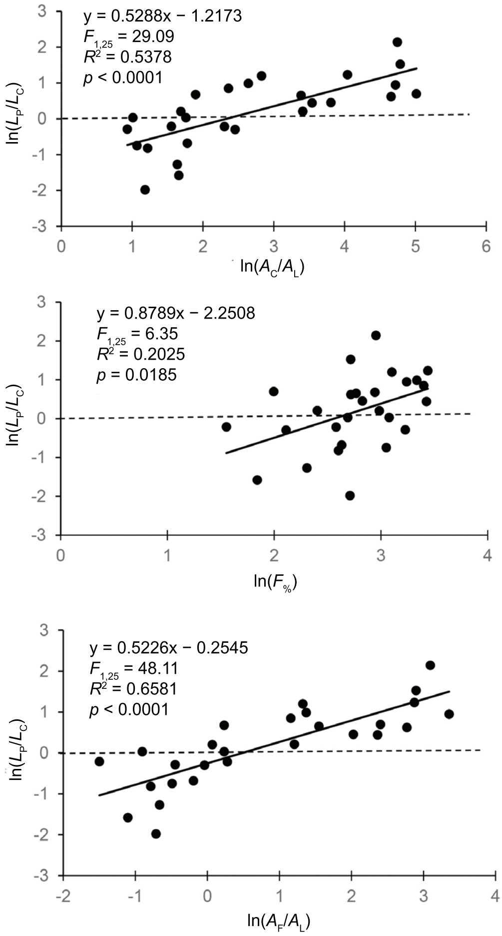

Figure 2. The effect of A_C/A_L (top), $F_{\%}$ (middle) and A_F/A_L (bottom) on L_P/L_C. The dotted horizontal line shows the level where $L_P = L_C$. The values are ln-transformed.

age of lakes (Ekholm *et al*. 2000, Rantakari *et al*. 2004, Mattsson *et al*. 2005, Röman *et al*. 2018). This was attributed to the relatively low $L_{\%}$ values in the studied catchments. The mean $F_{\%}$ of the catchments was 17.5%. According to the regression equation presented by Rekolainen (1989), such field coverage results in a P load of 34 kg km^{-2} a^{-1}. This was in good accordance with the estimated average P load entering our study lakes per unit area of the catchments (40 kg km^{-2} a^{-1}).

A_C/A_L, A_F/A_L and $F_{\%}$ had a significant effect on the L_P/L_C ratio. Thus the risk of exceeding the critical P load could be predicted with all three parameters. There are, however, several aspects that have to be taken into account. Together with their effect on L_P, A_C/A_L and A_F/A_L have an influence on L_C. This is because A_C/A_L is usually negatively correlated with the water residence time of lakes (Algesten *et al*. 2003, Kalff 2003). Accordingly, both A_C/A_L and A_F/A_L had a significant effect on q_s. Since L_C increases with increasing q_s, the effect of A_C/A_L and A_F/A_L on q_s attenuated their effect on L_P/L_C. When using A_C/A_L, it must also be considered that the catchment areas of inflowing streams are often used in areal extrapolation to estimate the water discharge and load from unmonitored catchments (Ekholm *et al*. 1997).

When predicting L_C, A_C/A_L had a higher coefficient of determination than A_F/A_L. For L_P, on the other hand, A_F/A_L had a higher coefficient of determination than A_C/A_L. These findings suggested that the leaching of P in relation to water

Table 3. Results from the regression analyses on the relationship of $F_{\%}$, A_C/A_L and A_F/A_L with L_C and epilimnetic P_{tot} concentration. The statistics are for ln-transformed values and statistically significant *p*-values are bolded.

Independent variable	Regression equation	$F_{1,25}$	R^2	p
Critical P load (L_C)				
A_C/A_L	y = 0.3936x + 4.8671	145.49	0.85	**< 0.001**
$F_{\%}$	y = 0.2425x + 5.2491	1.15	0.04	0.294
A_F/A_L	y = 0.3458x + 5.6336	108.32	0.81	**< 0.001**
Epilimnetic P_{tot}				
A_C/A_L	y = 0.2117x + 3.2123	4.17	0.14	0.052
$F_{\%}$	y = 0.9473x + 1.1654	15.93	0.39	**< 0.001**
A_F/A_L	y = 0.2760x + 3.5506	10.71	0.30	**0.003**

discharge increases more strongly with increasing A_F/A_L than with increasing A_C/A_L. This was explained by concentration differences. Water discharging from cultivated areas usually shows considerably higher concentrations of P compared with waters coming from areas with different land cover such as forests (Ekholm *et al.* 2000, Vuorenmaa *et al.* 2002).

When $F_{\%}$ was used as the predictor of L_P/L_C, the regression had a steeper slope but a lower coefficient of determination than with A_C/A_L or A_F/A_L. The steeper slope was explained by the insignificant effect of $F_{\%}$ on q_s and consequently, a weak effect on L_C. On the other hand, $F_{\%}$ does not account for the variability between the lake area and the catchment area, which resulted in a large variation and low R^2 value in the regression between $F_{\%}$ and L_P. In the present dataset for instance, Villikkalanjärvi and Pyhäjärvi (Orimattila) had a similar $F_{\%}$ in their catchments (31%) and almost similar catchment area. However, L_P/L_C was 3.43 for Villikkalanjärvi and 1.56 for Pyhäjärvi. This was because the area of Villikkalanjärvi was considerably smaller than that of Pyhäjärvi. Thus, although the catchments had the same percentage of cultivated land, A_F/A_L was considerably higher for Villikkalanjärvi (17.7) than for Pyhäjärvi (10.6). Due to the strong effects of cultivated areas on P load, this led to different L_P/L_C values.

A_F/A_L and $F_{\%}$ had a significant relationship with the epilimnetic P concentration amongst the study lakes, but A_C/A_L did not; which again highlighted the strong effect of agriculture on P load. The regressions for P concentration had considerably lower R^2 values than the regressions for external P load. This was expected, because compared with nitrogen and carbon concentrations in lakes, a smaller part of the variation in P concentration can be explained by catchment characteristics (Rantakari *et al.* 2004). P concentration in the water column is strongly regulated by numerous in-lake factors. Internal P load (i.e., recycling of P from the sediment to the water column) is an important water quality regulator in a large number of lakes (e.g., Søndergaard *et al.* 2003, Tammeorg *et al.* 2017). The intensity of internal P load is governed by numerous lake characteristics such as water depth, wind exposure, aquatic vegetation and activities of the biota (Horppila and Nurminen 2003, Søndergaard *et al.* 2003, Mazutzaki *et al.* 2007). Therefore, P concentration in the water often fluctuates independently on external P load. Consequently, when internal P load dominates, the Vollenweider (1976) model can fail in predicting the water quality (Ahlgren *et al.* 1988, Brett and Benjamin 2008).

The effect of internal P load could also be seen when comparing lake P concentrations and predictions on external P load (L_P). Critical P load (L_C) was exceeded when $A_F/A_L > 1.63$. This was the case in 13 out of the studied 27 lakes. The average P_{tot} concentration of these lakes was 71 µg l^{-1}. Of the 14 lakes with $A_F/A_L < 1.63$, the mean P_{tot} concentration was 41 µg l^{-1}. In three of these lakes (Savijärvi, Matalajärvi and Enäjärvi), P_{tot} concentration was considerably higher than on average in this group of lakes. For Matalajärvi and Savijärvi, this was explained by their low mean and maximum depths. In shallow lakes, internal load due to sediment resuspension is often intensive and the effect of internal load on nutrient concentration is strong, because the sediment surface:water column ratio is high (Søndergaard *et al*. 2003). Therefore, land use is a better water quality predictor for deep lakes than for shallow lakes (Nielsen *et al*. 2012). Accordingly, earlier studies in Matalajärvi and Savijärvi have indicated that the recycling of P from the sediment to the water column is very intensive (Mykkänen 2007, Lappalainen *et al*. 2013). Enäjärvi has a long history of intensive internal P load, which is due to the low P-binding capacity of the sediment (Salonen *et al*. 1993, Varjus 2015). If Matalajärvi, Savijärvi and Enäjärvi were excluded, the average P_{tot} concentration in the lakes with $A_F/A_L < 1.63$ was 25 µg l^{-1}, which was close to the 20 µg l^{-1} concentration threshold set by the Vollenweider (1976) model for lakes where $L_P < L_C$.

The present results suggested that if the aim is to assess the risk of exceeding the critical P load of a lake, A_F/A_L can be a better predictor than $F_{\%}$. The relationship between A_F/A_L and L_P/L_C was strong despite many factors excluded from the analysis. The slopes of the fields, soil texture and farm management practices can have a considerable impact on the P load from cultivated land (Johnes 1996, Ekholm *et al*. 2000, Kyllmar *et al*. 2006). Such data are required for accurate load estimates. The present results demonstrated, however, that if data for more complicated models are not available, A_F/A_L can be used as a simple tool to assess the risk of exceeding the critical nutrient load of lakes. Due to the simplicity of the approach, single A_F/A_L threshold values, such as 1.63 (calculated based on the present data) can probably be applied only for relatively restricted group of lakes. However, regional variability is a common phenomenon in models using land use data (Rantakari *et al*. 2004) and the threshold values have to be separately evaluated for each dataset. The results suggest that the estimated threshold can be applied to catchments with $F_{\%}$ varying from 5–31% and $L_{\%}$ (lake excluded) from 0–7%. Catchments having very different $F_{\%}$ and $L_{\%}$ than those used in the present study likely have different nutrient retention capacities and A_F/A_L thresholds. For lakes that have important sources of point load, the A_F/A_L tool must be applied with caution. In spite of this, A_F/A_L is a promising and simple, user-friendly tool for evaluating the risk of lake eutrophication based on land use information.

Conclusions

Our results showed that catchment area to lake area ratio (A_C/A_L), cultivated catchment area to lake area ratio (A_F/A_L) and percentage of cultivated land in the catchment ($F_{\%}$) can be used to predict the risk of exceeding the critical P load. However, A_F/A_L had the best predicting power. This was because it contained information on both land use and catchment area variations. Using the data of 27 lakes located in southern Finland, we showed that critical P load was exceeded when $A_F/A_L > 1.63$. A_F/A_L can be a useful simple tool for evaluating the risk of lake eutrophication.

Acknowledgements: The study was supported by the Academy of Finland (project #263365) and Maa- ja Vesiteknii-kan Tuki ry (project #29159). We acknowledge Prof. Erik Jeppesen for useful discussions on the topic of the manuscript.

References

Aaltonen H. & Jutila H. 2006. *Loppijärven kuormitusselvitys*. Hämeenlinnan seudullisen ympäristötoimen monisteita 5.

Algesten G., Sobek S., Bergström A.-K., Ågren A., Tranvik L. J. & Jansson M. 2003. Role of lakes for organic carbon cycling in the boreal zone. *Global Change Biology* 10: 141–147.

Ahlgren I., Frisk T. & Kamp-Nielsen L. 1988. Empirical and theoretical models of phosphorus loading, retention and concentration vs. lake trophic state. *Hydrobiologia* 170: 285–303.

Anonymous 2015. *Hämeen vesienhoidon toimenpideohjelma vuoteen*. Elinkeino-, liikenne- ja ympäristökeskus, Häme.

Arhonditsis G.B., Qian S.S., Stow C.A., Lamon E.C. & Reckhow K.H. 2007. *Ecological Modelling* 208: 215–229.

Bechmann M.E., Berge D., Eggestad H.O. & Vandsemb S.

M. 2005. Phosphorus transfer from agricultural areas and its impact on the eutrophication of lakes — two long-term integrated studies from Norway. *Journal of Hydrology* 304: 238–250.

Bennion H., Hilton M., Hughes J., Clark J., Hornby D., Fozzard I., Phillips G. & Reynolds G. 2005. The use of a GIS-based inventory to provide a national assessment of standing waters at risk from eutrophication in Great Britain. *Science of the Total Environment* 344: 259–273.

Brett M.T. & Benjamin M.M. 2008. A review and reassessment of lake phosphorus retention and the nutrient loading concept. *Freshwater Biology* 53: 194–211.

Canfield D.E. & Bachmann R.W. 1981. Prediction of total phosphorus concentrations, chlorophyll a, and Secchi depths in natural and artificial lakes. *Canadian Journal of Fisheries and Aquatic Sciences* 38: 414–423.

Carpenter S.R., Caraco N.F., Correll D.L., Howarth R.W., Sharpley A.N. & Smith V.H. 1998. Nonpoint pollution of surface waters with phosphorus and nitrogen. *Ecological Applications* 8: 559–568.

Dillon P.J. & Kirchner W.B. 1975. The effects of geology and land use on the export of phosphorus from watersheds. *Water Research* 9: 135–148.

Dillon P.J. & Rigler F.H. 1975. A simple method for predicting the capacity of a lake for development based on lake trophic status. *Journal of the Fisheries Research Board of Canada* 32: 1519–1531.

Ekholm P., Malve O. & Kirkkala T. 1997. Internal and external loading as regulators of nutrient concentrations in the agriculturally loaded Lake Pyhäjärvi (southwest Finland). *Hydrobiologia* 345: 3–14.

Ekholm P., Kallio K., Salo S., Pietiläinen O.-P., Rekolainen S., Laine Y. & Joukola M. 2000. Relationship between catchment characteristics and nutrient concentrations in an agricultural river system. *Water Research* 34: 3709–3716.

Eloranta P. 2005. Järvien kunnostuksen biologiset perusteet. In: Ulvi T. & Lakso E. (eds.), *Järvien kunnostus*, Edita Prima Oy, Helsinki, pp. 13–28.

Hagman A.M. 2010. *Espoon Bodominjärven kunnostussuunnitelma*. Report 26, Uudenmaan elinkeino-, liikenne- ja ympäristökeskuksen julkaisuja.

Hagman A.M. 2011. *Sipoon Savijärven kunnostussuunnitelma*. Uudenmaan elinkeino-, liikenne- ja ympäristökeskuksen julkaisuja. Report 20.

Hagman A.M. 2012. *Hiidenveden kunnostus 2012–2015 — hanke hiidenveden kunnostus- ja hoitosuunnitelma*. Ramboll.

Heckrath G., Bechmann M., Ekholm P., Ulėn B., Djodjic F. & Andersen H.E. 2008. Review of indexing tools for identifying high risk areas of phosphorus loss in Nordic catchments. *Journal of Hydrology* 349: 68–87.

Horppila J. & Nurminen L. 2003. Effects of submerged macrophytes on sediment resuspension and internal phosphorus loading in Lake Hiidenvesi (southern Finland). *Water Research* 37: 4468–4474.

Huuhko J. & Hanski A. 2012. *Tuusulan kunta*. *Rusutjärven kunnostus- ja hoitosuunnitelma 2012–2022*. Report 40. Ramboll.

Janse J. H., Scheffer M., Lijklema L., Van Liere L., Sloot J. S. & Mooij W. M. 2010. Estimating the critical phosphorus loading with the ecosystem model PClake: sensitivity, calibration and uncertainty. *Ecological Modelling* 221: 654–665.

Johnes P. J. 1996. Evaluation and management of the impact of land use change on the nitrogen and phosphorus load delivered to surface waters: the export coefficient modelling approach. *Journal of Hydrology* 183: 323–349.

Jones A.S., Horsburgh J.S., Mesner N.O., Ryel R.J., & Stevens D.K. 2012. Influence of sampling frequency on estimation of annual total phosphorus and total suspended solids loads. *Journal of the American Water Resources Association* 48: 1258–1275.

Jutila H. & Salminen P. 2006. *Hämeenlinnan Katumajärven tila ja kuormitus* Hämeenlinnan seudullisen ympäristötoimen julkaisuja. Report 2

Järveläinen J., Malin I., Mäyränpää R. & Kotakorpi M. 2016. Kymijärven ravinnekuormitus. *Report on riverine loading*. Lahden kaupunki. Tekninen ja ympäristötoimi, 24 p

Kaipainen H., Bilaletdin Ä., Perttula H., Heino H., Mäkelä H. & Viitaniemi S. 2002. *Hauhon reitin kuormitusselvitys*. Pirkanmaan ympäristökeskus, Tampere.

Kalff J. 2003. *Limnology: inland water ecosystems*. Prentice-Hall Inc., Upper Saddle River, NJ.

Karvonen T. 2007. *Matalajärven kuormitusselvitys* (1/2007). *Espoon Ympäristökeskuksen Monistesarja*.

Kauppinen E. 2007. *Harvanjärven alustava kunnostussuunnitelma*. Water Eco Ltd. Report 69.

Keto A. & Sammalkorpi I. 2009. *Loppijärven säännöstelyn kehittämismahdollisuudet ja kunnostustarpeen arviointi*. Suomen ympäristökeskus.

Kirchner W.B. & Dillon P.J. 1975. An empirical method of estimating the retention of phosphorus in lakes. *Water Resources Research* 11: 182–183.

Knuuttila S., Pietiläinen O.-P. & Kauppi L. 1994. Nutrient balances and phytoplankton dynamics in two agriculturally loaded shallow lakes. In: Mortensen E., Jeppesen, E., Søndergaard M. & Kamp-Nielsen L. (eds.), *Nutrient dynamics and biological structure in shallow freshwater and brackish lakes*. Springer, Netherlands, pp. 359–369.

Kontio H. 2011. *Äimäjärven ravinnetase ja hydrologia*. Hämeen elinkeino-, liikenne- ja ympäristökeskuksen julkaisuja. Report 2.

Kortelainen P. 1993. Content of total organic carbon in Finnish lakes and its relationships to catchment characteristics. *Canadian Journal of Fisheries and Aquatic Sciences* 50: 1477–1483.

Kyllmar K., Carlsson C., Gustafson A., Ulén B. & Johnsson H. 2006. Nutrient discharge from small agricultural catchments in Sweden. Characterization and trends. *Agriculture Ecosystems & Environment* 115: 15–26.

Lappalainen K. M. 1998. *Pusulanjärven ainetaselaskelmat ja hapetussuunnitelma*. Uudenmaan ympäristökeskus ja Vesi-Eko Oy, Finland

Lappalainen J., Vinni M. & Malinen T. 2013. Consumption of crucian carp (*Carassius carassius* (L.), 1758) by restocked pike (*Esox lucius* (L.), 1758) in a lake with frequent winter hypoxia. *Journal of Applied Ichthyology* 29: 1286–1291.

Matsuzaki S. S., Usio N., Takamura N. & Washitani I. 2007.

Effects of common carp on nutrient dynamics and littoral community composition: roles of excretion and bioturbation. *Fundamental and Applied Limnology* 168: 27–38.

Mattsson T., Kortelainen P. & Räike A. 2005. Export of DOM from boreal catchments: impacts of land use cover and climate. *Biogeochemistry* 76: 373–394.

Meeuwig J. & Peters R.H. 1996. Circumventing phosphorus in lake management: a comparison of chlorophyll a predictions from land-use and phosphorus loading models. *Canadian Journal of Fisheries and Aquatic Sciences* 53: 1692–1694.

Muukkonen P. 2010. *Tuusulanjärven vesitase ja ravinnetaseet vuosina 1990–2009*. Uudenmaan elinkeino-, liikenne- ja ympäristökeskuksen julkaisuja.

Mykkänen J. 2007. *Ulkoinen ravinnekuormitus ja sedimentistä vapautuvat ravinteet Espoon Matalajärvessä* (Master's thesis). Helsinki Technical University.

Mäkelä T, 2016. Tammelan Oksjärven kunnostus- ja hoitosuunnitelma (Bachelor's thesis). Häme University of Applied Sciences.

Nielsen A., Trolle D., Søndergaard M., Lauridsen T. L., Bjerring R., Olesen J. E. & Jeppesen E. 2012. Watershed land use effects on lake water quality in Denmark. *Ecological Applications* 22: 1187–1200.

Närvänen A., Puronummi N. & Jansson H. 2003. Vesistökuormitus Etelä-Pirkanmaan alueella. Maa- ja elintarviketalouden tutkimuskeskus. *MTT:n selvityksiä* 41.

Ojanen T. 1979. *Tuusulanjärven typpi- ja fosforitase 1974–1979* (Master's thesis). University of Helsinki.

Paloheimo A. 2010. Köyliönjärvi. Tila, kuormitus ja kunnostus. *Pyhäjärvi-Instituutin julkaisuja* Series B no. 15. ISBN 978-952-9682-53-9.

Palviainen M., Lehtoranta J., Ekholm P., Ruoho-Airola T. & Kortelainen P. 2015. Land cover controls the export of terminal electron acceptors from boreal catchments. *Ecosystems* 18: 343–358.

Prairie Y.T. & Kalff J. 1986. Effect of catchment size on phosphorus export. *Water Resources Bulletin* 22: 465–470.

Pulkkinen J. 2014. *Joroisselän Kuormitusselvitys*. Etelä-Savon elinkeino-, liikenne- ja ympäristökeskus. Report 62.

Rantakari M., Kortelainen P., Vuorenmaa J., Mannio J. & Forsius M. 2004. Finnish lake survey: the role of catchment attributes in determining nitrogen, phosphorus, and organic carbon concentrations. *Water, Air and Soil Pollution: Focus* 4: 683–699.

Reckhow K.H. 1979. Uncertainty analysis applied to Vollenweider's phosphorus loading criterion. *Water Pollution Control Federation* 51: 2123–2128.

Reckhow K.H., Beaulac M.N. & Simpson J.T. 1980. *Modeling phosphorus loading and lake response under uncertainty: a manual and compilation of export coefficients*. U.S. Environmental Protection Agency, Washington, D.C.

Reed-Andersen T., Carpenter S. R. & Lathrop R. 2000. Phosphorus flow in watershed-lake ecosystem. *Ecosystems* 3: 561–537.

Rekolainen S. 1989. Phosphorus and nitrogen load from forest and agricultural areas in Finland. *Aqua Fennica* 19: 95–107.

Riihimäki A. 2008. *Sipoon S*avijärven rehevöitymishistorian kartoitus piilevien avulla (Master's thesis). University of Helsinki.

Röman E., Ekholm P., Tattari S., Koskiaho J. & Kotamäki N. 2018. Catchment charateristics predicting nitrogen and phosphorus losses in Finland. *River Research and Applications* 34: 397–405.

Salo J. & Harjula H. 2012. *Hirvijärven kuormitus ja kunnostamistoimenpiteet*. Hirvijärven suojeluyhdistys ry, Hämeen ELY-keskus. Lapin Vesitutkimus Oy, Finland

Salonen V.-P., Alhonen P., Itkonen A. & Olander H. 1993. The trophic history of Enäjärvi, SW Finland, with special reference to its restoration problems. *Hydrobiologia* 268: 147–162.

Schindler D.W. 1977. Evolution of phosphorus limitation in lakes. *Science* 195: 260–262.

Schindler D.W. 2006. Recent advances in the understanding and management of eutrophication. *Limnology and Oceanography* 51: 356–363.

Sharpley A.N., McDowell R.W., Weld J.L. & Kleinman P. 2001. Assessing site vulnerability to phosphorus loss in an agricultural watershed. *Journal of Environmental Quality* 30: 2026–2036.

Skippari K., Heino H., Kaipainen, H. & Bilaletdin Å. 2003. *Kyrösjärven, Parkanonjärven ja Jämijärven vesiensuojelusuunnitelman seurantatutkimus*. Pirkanmaan ympäristökeskus. Alueelliset ympäristöjulkaisut. Report 329

Smith V. H. 2003. Eutrophication of freshwater and coastal marine ecosystems – a global problem. *Environmental Science and Pollution Research* 10: 126–139.

Søndergaard M., Jensen J.P. & Jeppesen E. 2003. Role of sediment and internal loading of phosphorus in shallow lakes. *Hydrobiologia* 506–509: 135–145.

Soranno P.A., Hubler S., Carpenter S.R. & Lathrop R.C. 1996. Phosphorus loads to surface waters: a simple model to account for spatial pattern of land use. *Ecological Applications* 6: 865–878.

Tammeorg O., Möls T., Niemistö, J., Holmroos H. & Horppila J. 2017. The actual role of oxygen deficit in the linkage of the water quality and benthic phosphorus release: Potential implications for lake restoration. *Science of the Total Environment* 599–600: 732–738.

Taponen T. 1997. *Vihdin Enäjärven ulkoinen ja sisäinen fosfori-ja typpikuormitus 1994–95* (Master's thesis). University of Helsinki.

Tong S. T. Y. & Chen W. 2002. Modeling the relationship between land use and surface water quality. *Journal of Environmental Management* 66: 377–393.

Tossavainen T. 2014. *Lieksan Vuonisjärven vedenlaatu, kuormitus, pohjasedimentti, pohjaeläimistö, kalasto ja makrofyytit*. Kunnostussuunnitelman esitutkimus. Karelia University of Applied Sciences. Publication C 11

Valjus J. 2011. Siuntionjoen vesistön yhteistarkkailun yhteenveto. *Suppea tarkkailuvuosi 2010*. Länsi-Uudenmaan vesi ja ympäristö.

Valjus J. 2012. Siuntionjoen vesistön yhteistarkkailun yhteenveto. *Suppea tarkkailuvuosi 2011*. Länsi-Uudenmaan vesi ja ympäristö.

Varjus T. 2015. *Seurantatutkimus Vihdin Enäjärven fosforinpidätyskyvyn kehityksestä* (Master's thesis). University of Helsinki.

Veith T.L., Sharpley A.N., Weld J.L. & Gburek W.J. 2005. Comparison of measured and simulated phosphorus losses with indexed site vulnerability. *Transactions of the ASAE* 48: 557–565.

Ventelä A.M., Tarvainen M., Helminen H. & Sarvala J. 2007. Long-term management of Pyhäjärvi (southwest Finland): eutrophication, restoration — recovery? *Lake and Reservoir Management* 23: 428–438.

Vollenweider R.A. 1976. Advances in defining critical loading levels for phosphorus in lake eutrophication. *Memorie dell'Istituto Italiano di Idrobiologia*. 33: 53–83.

Vuorenmaa J., Rekolainen S., Lepistö A., Kenttämies K. & Kauppila P. 2002. Losses of nitrogen and phosphorus from agricultural and forest areas in Finland during the 1980s and 1990s. *Environmental Monitoring and Assessment* 76: 213–248.